63-3-1

AFCRL - 63 - 288

RESEARCH IN INFRARED INTERFEROMETRY AND OPTICAL MASERS

Bruce Billings

Baird-Atomic, Inc.
33 University Road
Cambridge, Massachusetts

Contract No. AF 19(604)-2264

FINAL REPORT

VOLUME II

21 February 1963

Project 7670

Task 76703

Geophysics Research Directorate
Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

ARCRL-63-288

RESEARCH IN INFRARED INTERFEROMETRY AND OPTICAL MASERS

Bruce Billings

Baird-Atomic, Inc.
33 University Road
Cambridge 38, Massachusetts

Contract No. AF 19 (604)-2264

FINAL REPORT

VOLUME II

21 February 1963

Project 7670

Task 76703

Geophysics Research Directorate
Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

VOLUME II

MASER STUDIES

TABLE OF CONTENTS

VOLUME II

MASER STUDIES

1. INTRODUCTION

The remainder of this report is devoted to an investigation of circularly polarized optical masers and some macroscopic effects associated with such maser beams.

Polarization of laser output has been reported in the literature. In the case of the crystal laser, the polarization state of the output radiation depends critically on the way the crystal is cut with respect to the optic axis. The output of a gas laser apparently is also partially linearly polarized, but in a direction which is entirely random. The direction of polarization thus seems to depend on the orientation of the polarization vector of the first random photon that initiates laser action

Of primary concern for our purposes are the design characteristics of a laser which does not resonate simultaneously for the four possible state vectors, as used by Yang.[1]

---

[1] Yang, C.N., Phys. Rev. 77, 242 (1950)

2. CHARACTERISTICS OF PHOTONS WITHIN THE LASER CAVITY

The state of a photon in a cavity can be specified according to two indices. In general, however, we shall be concerned with two photons at a time, one traveling in the +z direction, the other the -z direction. We shall therefore use the notation of Yang, where the four possible state vectors are symbolized by ψRR, ψRL, ψLR, ψLL. The first index refers to the CP state of the photon propagating in the +z direction, the second index to the CP state of the photon going in the -z direction. For ease in notation we shall use the abbreviation RCP and LCP for the terms "right- and left-circularly polarized", respectively.

For an RCP photon traveling in the +z direction, the electric field can be described by:

$$(E_x)_+^R = E_o \cos (kz - \omega\tau + \delta_+^R)$$

$$(E_y)_+^R = E_o \sin (kz - \omega\tau + \delta_+^R)$$

For an RCP photon in the -z direction, we have:

$$(E_x)_-^R = E_o \cos (-kz - \omega\tau + \delta_-^R)$$

$$(E_y)_-^R = -E_o \sin (-kz - \omega\tau + \delta_-^R)$$

Here δ_+^R, δ_-^R are the arbitrary phases of the photons. However, since in our problem the photons propagating in the -z direction are obtained by reflection of the photons propagating in the +z direction, δ_+ and δ_- are not independent. The relationship depends on the nature of the reflecting surface.

It is clear that the other two photon states may be described by:

$$(E_x)_+^L = E_o \cos (kz - \omega\tau + \delta_+^L)$$

$$(E_y)_+^L = E_o \sin (kz - \omega\tau + \delta_+^L)$$

and:

$$(E_x)_-^L = E_o \cos(-kz - \omega\tau - \delta_-^L)$$

$$(E_y)_-^L = E_o \sin(-kz - \omega\tau + \delta_-^L)$$

Yang now introduces the rotation operator R_ϕ for rotations about the z-axis. The eigen values of R_ϕ are:

$$R_\phi \psi^{RR} = \psi^{RR}$$

$$R_\phi \psi^{LL} = \psi^{LL}$$

$$R_\phi \psi^{RL} = e^{2i\phi} \psi^{RL}$$

$$R_\phi \psi^{LR} = e^{-2i\phi} \psi^{LR}$$

Thus, according to the rules of quantum mechanics, the states ψ^{RR} and ψ^{LL} are associated with zero net angular momentum, while the states ψ^{RL} and ψ^{LR} have +2 units and -2 units of angular momentum, respectively.

Now it is clear that if the object is to obtain, say, RCP radiation from one end of the laser, any linear superposition such as

$$\psi^{RR} + \psi^{RL} \tag{1}$$

will serve. Such a state is characterized by the property that only RCP photons propagate in the +z direction. Thus, from equation (1), only RCP photons can emerge from the +z end of the laser.

On the other hand, if one wishes to investigate the angular momentum effects within the laser itself, the state which must be isolated is either ψ^{RL} or ψ^{LR}. While it is true that an admixture of ψ^{RR} has no angular momentum effect, this state will tend to depopulate the levels of interest and thus weaken the effect being investigated.

3. ISOLATION OF A SINGLE PHOTON STATE

3.1 Zeeman Effect

Perhaps the simplest method, conceptually, for causing a laser to operate in a single circularly polarized (CP) mode, is to utilize the Zeeman effect; that is, to split the $\ell = 1$ magnetic sublevels, so that only one of the three magnetic transitions overlaps appreciably with the resonance linewidth of the cavity. To accomplish this, the Zeeman splitting must be several times the Doppler width of the spectral line. The Doppler width is proportional to v/c where v is the thermal velocity and c is the velocity of light; hence the Doppler width is given by:

$$\frac{\Delta \nu}{\nu} \sim \sqrt{\frac{3kT}{2Mc^2}}$$

where $\frac{3kT}{2}$ is the average thermal energy, and Mc^2 is the rest energy of the nucleus. On the other hand, the Zeeman splitting is given by:

$$\Delta \nu_z = \mu H$$

where μ is the magnetic moment of the electron, and H is the magnetic field strength. Thus, we would require:

$$\mu H \simeq q\nu \sqrt{\frac{kT}{Mc^2}}$$

where q is a dimensionless quantity of the order of 3 to 5. We introduce the following approximate values:

$$\mu \sim 1 \text{ megacycle/gauss}$$

$$\nu \sim 10^9 \text{ megacycles/sec}$$

$$kT \sim 1/40 \text{ ev (room temperature)}$$

$$Mc^2 \sim 20 \times 10^9 \text{ ev (for } Ne^{20})$$

We then find that the magnetic field must be of the order of 3000 to 4000 gauss. While such fields are of course obtainable in practice, it seems more desirable to investigate the use of the Zeeman effect in a more efficient way, namely, through the Faraday effect.

3.2 Faraday Effect

Since the Zeeman effect in certain glasses produces different indices of refraction for RCP and LCP light, the resonant frequency of the cavity can be made different for these two modes of polarization. With this technique, the energy levels of the laser atoms are left undisturbed, but the effective optical dimensions of the cavity are different for the two transitions $m = \pm 1$. This enables the use of much smaller magnetic fields to produce the same result.

The state ψ^{RL} is differentiated from all other states by its behavior under the operation R_ϕ. This suggests that an optical element be introduced which provides both an axis (coinciding with the laser axis) and a sense along the axis. Such an element would be a Faraday active element.

The Faraday element consists of a carefully chosen glass in which a magnetic field is imposed. The magnetic field in this case must be along the axis of the laser and directed in the +z direction. The operation of the element then results from the longitudinal Zeeman effect in the glass. The index of refraction of any material can be written, approximately, as:

$$n - 1 = \frac{Nf\, e^2/m}{2\pi\,(\nu_o^2 - \nu^2)}$$

where ν is the frequency of the incident light, ν_o is the nearest absorption frequency in the material, N is the density of absorbers, f the oscillator strength, and e and m have their usual atomic meanings.

In the event that the transition at frequency ν_o is split by the Zeeman effect, the index of refraction changes. The splitting is given by:

$$\Delta\nu = \frac{e}{\Delta\,\pi\, mc}\, H$$

so that we obtain, for RCP_+ and LCP_+ photons:

$$n - 1 = \frac{1/2 \, Nf \, e^2/m}{2\pi \left[(\nu_o + \Delta\nu)^2 - \nu^2\right]}$$

$$n - 1 = \frac{1/2 \, Nf \, e^2/m}{2\pi \left[(\nu_o - \Delta\nu)^2 - \nu^2\right]}$$

The component of radiation with the smaller wavelength, corresponding to $\nu_o + \Delta\nu$, is always that component which rotates in the same sense as the current which would cause the external field. Thus, on propagating in the +z direction, the RCP photon has the shorter wavelength; while for photons propagating in the -z direction, the LCP photons have the shorter wavelength.

Now, in the laser, a photon is to be reflected back and forth many times, with little loss at each reflection. It is necessary, therefore, that the reflection be from the surface of a high index medium, for example, a metal. Consequently, on reflection, a phase change is introduced in the components of the electric field; we define, therefore, a reflection operator P (not to be confused with the inversion operator of Yang). The operation P reverses the direction of propagation ($z \to -z$) <u>and</u> changes the sign of $\vec{E}$. Using equations (1-4), we see that:

$$P(\vec{E}_+^R) = -\vec{E}_-^L$$

$$P(\vec{E}_+^L) = -\vec{E}_-^R$$

or, metallic reflection changes RCP into LCP, and vice versa.

We now specify more precisely what we mean by a "two photon state". Physically, there is only one photon, and we consider it before and after reflection. Thus, the introduction of a metallic mirror in the laser system immediately picks out the two states ψ^{RL} and ψ^{LR}. The states ψ^{RR} and ψ^{LL}, under this definition, are excluded. In operator language, we are restricted to eigen states of the operator P. The operator P has the effect of changing $R \to L$, $L \to R$, <u>and</u>

interchanging indices. There is, in addition, a change in sign, which is unimportant, as it only counts whether the number of reflections is odd or even. Thus,

$$P\,\psi^{RL} = -\psi^{RL}$$

$$P\,\psi^{LR} = -\psi^{LR}$$

We must now inquire whether the Faraday element can in principle distinguish between the two remaining states. The significant property is effective length of the laser. If we imagine a configuration as shown in figure II-1, we must

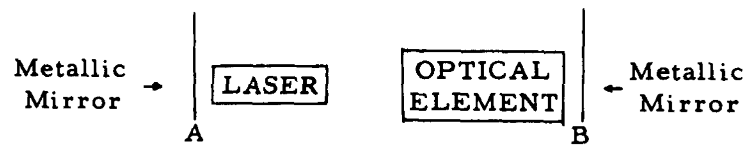


Figure II-1

must consider a photon starting at A, reflected at B, and returning to A. The effective optical path for the ψ^{RL} state is then given by

$$D^{RL} = 2n_o\,\ell_o + 2n < \ell_F$$

while for the state ψ^{LR}, it is given by

$$D^{LR} = 2n_o\,\ell_o + 2n > \ell_F$$

where ℓ_o is the length of laser, ℓ_F is the length of Faraday element, n_o is the optical index of laser, and $n >$ and $n <$ are the optical indices of the Faraday elemen

It is seen from the preceding equations that the Faraday optical element does indeed distinguish the states ψ^{RL} and ψ^{LR}. By careful choice of the Faraday glass, magnetic field strength, etc., the cavity can be adjusted to resonate in the state ψ^{RL} and not in the state ψ^{LR}. It is perhaps of some interest to note that by means of quarter-wave plates, the states ψ^{RR} and ψ^{LL} can be reached, and the states ψ^{RL}, ψ^{LR} excluded. If we place in front of each mirror a quarter-wave plate, the total effect is to change an $(RCP)_+$ photon into an $(RCP)_-$ photon. This can be seen by examining the electric field components at each stage; thus, incident on the quarter-wave plate we have an $(RCP)_+$ photon, viz:

$$E_x = E_o \cos (kz - \omega\tau + \phi)$$

$$E_y = E_o \sin (kz - \omega\tau + \phi)$$

where ϕ is an arbitrary phase angle. After passing through the quarter-wave plate, but before reflection, we have

$$E_x = E_o \cos (kz' - \omega\tau' + \phi')$$

$$E_y = E_o \sin (kz' - \omega\tau' + \phi' + \pi/2$$

After reflection, we have

$$E_x = E_o \cos (-kz' - \omega\tau' + \phi')$$

$$E_y = E_o \sin (-kz' - \omega\tau' + \phi' + \pi/2)$$

And after another passage through the quarter-wave plate

$$E_x = -E_o \cos (-kz - \omega\tau'' + \phi'')$$

$$E_y = -E_o \sin (-kz - \omega\tau'' + \phi'' + \pi)$$

$$= +E_o \sin (-kz - \omega\tau'' + \phi'')$$

Thus, the combination of quarter-wave plate plus mirror is equivalent to an operator F', which changes $z \rightarrow -z$, $L \rightarrow L$, $R \rightarrow R$, and interchanges indices. It is seen that ψ^{RR} and ψ^{LL} are eigen states of F' with eigen value -1.

It will also be seen that the Faraday element no longer distinguishes between ψ^{RR} and ψ^{LL}. For the state ψ^{RR}, the effective length of the cavity is

$$D' = 2n_o \ell_o + (n> + n<) \ell_F + 2n_{1/4} \ell_{1/4}$$

where $n_{1/4}$ and $\ell_{1/4}$ refer to the quarter-wave plate. Since this equation is symmetric between n> and n<, the effective length is the same for both states. Hence, any linear combination of ψ^{RR} and ψ^{LL} becomes a normal mode for the laser cavity. In any event, since these staes have no angular momentum, they are of less interest.

4. MACROSCOPIC EFFECTS ASSOCIATED WITH CP OPERATION OF A LASER

Under the general heading of the macroscopic detection of polarized laser beams, the following discussion concerns the production of an intense polarized beam and its absorption in a thin disc. The object of this discussion is to determine whether it is feasible to impart a measurable radiation torque to the disc. This is the analogue with respect to angular momentum of a light pressure experiment with regard to linear momentum.[2]

The primary result of the present proposal would be the improvement and extension of the classic experiment of R.A. Beth[3], in which he made a measurement of the angular momentum of light by altering linearly polarized light to circular polarization in quarter-wave plates, and measuring the torque on the plates. This source was a tungsten filament heated to a maximum of 2700° absolute. The vastly greater intensity available from a laser in a narrow frequency band and narrow solid angle will allow a large accurately-known intensity and frequency to be absorbed or altered in polarization. The millisecond pulsing possible will further enhance the effect above the background, due to fluctuations of the molecular pressures and ambient temperatures.

The possibility of mechanical monitoring of polarization may possibly have application to communications and specialized experiments of other types. There are many ways of producing a polarized laser beam. The insertion of a Faraday medium in the cavity has already been discussed. As the beam must be used externally for this application, and as intensity is important, we will instead consider the linearly polarized beam produced by a ruby laser. As has already been noted, the experiment may be performed as well with a linearly polarized beam as with one circularly polarized.

---

[2] It should be noted that only marginal light pressure experiments have been performed in the laboratory. There would be many advantages in such an experiment to the use of a laser source - due to the collimation and monochromaticity of the beam, and its pulsed nature.

[3] R. A. Beth, Phys. Rev. 50, 115 (1936)

In figure II-2, the Zeeman split ruby lines contributing to the R radiation are shown.[4]

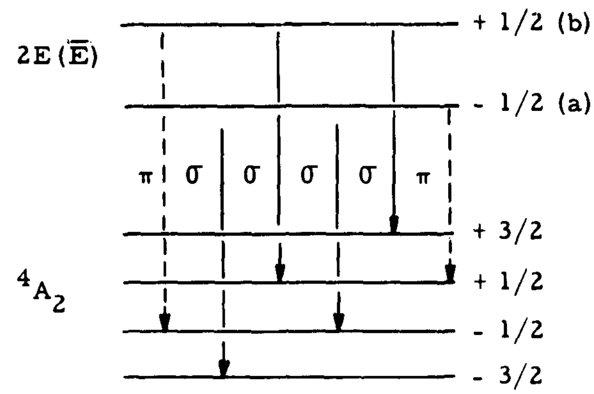


Figure II-2

It is important to note that the upper 2E(Ē) level is split by the trigonal symmetry of the crystal lattice coupled to the spin-orbit interaction of the Cr^+ ion. The oxygen octahedron is stretched along a threefold symmetry axis, presenting a distorted field to the Cr^+ ion, breaking the degeneracy. Thus, even in the absence of an external magnetic field, the orientation of the radiation with respect to the optic axis is of importance and polarization is possible and predicted. For the R_1 line at 6934Å [transitions from the lower 2E(Ē) line to the degenerate ground state quadruplet] the radiation is linearly polarized in a plane perpendicular to the optical axis. This has been experimentally verified[5] by observing the polarization of a laser beam from rods cut at different angles to the optics axis. For other than the zero angle between the rod and optics axes, almost 100 percent polarization in

[4] The ruby R spectrum is discussed by A. L. Schawlow, "Advances in Quantum Electronics", Columbia University Press (1961), p. 50.

S. Sugano and Y. Tanabe, J. Phys. Soc., Japan 13, 880 (1958).

[5] D. F. Nelson and R. J. Collins, "Advances in Quantum Electronics", Columbia University Press (1961), p. 79.

the direction perpendicular to the plane of the axes was found. No polarization was found in the 0 degree case. The linearly polarized light may be passed through a quarter waveplate, and a circularly polarized beam produced with little loss of intensity, giving a torque to the plate, and usable for further transmission or absorption. The Zeeman splitting of the ground state shown produces the usual α and π components, where the α components would show circular polarization if observed along the optic axis. This direct production of a circularly polarized beam may prove preferable if the ruby laser proves to be a more intense source of R radiation when the rod is cut along the optic axis.

A photon, circularly polarized along its direction of travel has a magnetic quantum number $M = \pm 1$, and thus a component of spin in that direction of $\pm h$. As the energy of the photon is given by $h\omega$, the ratio of the available component of angular momentum to the energy of each quantum, and hence of the polarized beam, is ω^{-1}. Thus a beam carrying n watts of power carries $\frac{n}{\omega}$ joule-second of angular momentum per second, if ω is measured in cycles per second. Thus, for the ruby line

$$\left(\text{using } \omega = \frac{2\pi c}{\lambda} = \frac{2\pi \times 3 \times 10^{8}}{7 \times 10^{-7}} = 3 \times 10^{15} \text{ cycles/sec}\right)$$

we have an angular momentum radiation rate of

$$\frac{n}{3 \times 10^{15}} \text{ Joules-sec/sec} = \frac{n}{3 \times 10^{15}} \times 10^{7} \text{ erg/sec/sec}$$

$$= 3 \times 10^{-8} \text{ n gm cm}^{2} \text{ sec}^{-1}\text{/sec}$$

$$= 3 \times 10^{-8} \text{ n dyne-cm torque}$$

This is to be compared with the 6×10^{-9} dyne-cm torque available in R. A. Beth's experiment.[3] If this were to be absorbed by an aluminum disc of 1 cm radius and 0.01 cm thickness, whose moment of inertia is 0.02 gm cm^2, it would impart an angular frequency of 1.5×10^{-6} n sec^{-1} per second. Ruby laser power has been increasing rapidly. A year ago, 5 kw peak power was obtained in a 1/2 m-second burst delivering one Joule of energy.[6] This would impart an angular frequency of 1.5×10^{-6} sec^{-1} per burst to the disc. The repetition rate possible may determine the feasibility of the experiment. A mechanical resonance technique should be applicable.

[6] T. H. Maiman, "Advances in Quantum Electronics" (1961), p. 91.

5. NUMERICAL ESTIMATES OF MACROSCOPIC EFFECTS

Below we develop some of the details required for an understanding of the magnetic field that can be developed by the polarization or alignment of atoms in a CP laser. The atomic polarization developed in optical pumping experiments is observed by resonance methods in which the atoms are disoriented by means of an r-f field, altering absorption properties at resonance. It is our purpose to determine if the direct measurement of the magnetic field due to atomic polarization is feasible.

5.1 Magnetic Field of a Polarized Gaseous Sample

Consider the magnetic field of a right cylinder of length L and cross sectional area A, filled with a gas containing N_{I_z} atoms aligned with magnetic quantum number I_z and with magnetic moment M_{I_z}. The effect is additive for different states I_z. Internal to the cylinder we have

$$B_{int} = \mu_o M_o$$

where the polarization density

$$M_o = \frac{N_{I_z}}{LA} M_{I_z}$$

Therefore the flux through any curve encircling the cylinder is given by

$$\phi_{int} = \mu_o M_o A \mu_o \frac{N_{I_z}}{L} M_{I_z}$$

Further, we have

$$M_{I_z} = \frac{e h}{2 M_e c} g I_z$$

where the detailed atomic structure is buried in the g factor which has order of magnitude unity. M_e is the electronic mass, e the electronic change, and h and c have their usual meaning.

Substituting

$$\frac{h}{M_e c} = 3.9 \times 10^{-13} \text{ meters}$$

$$\mu_o = 4\pi \times 10^{-7} \text{ henry/meter}$$

$$c = 3 \times 10^{8} \text{ meters sec}$$

$$e = 1.6 \times 10^{-19} \text{ coulombs}$$

and with a length of L meters,

$$\phi_{int} = 1.2 \times 10^{-29} \frac{N_{I_z} \, g \, I_z}{L} \; \frac{\text{coulomb-henry}}{\text{sec}}$$

$$= 1.2 \times 10^{-29} \frac{N_{I_z} \, g \, I_z}{L} \text{ webers}$$

$$= 1.2 \times 10^{-29} \frac{N_{I_z} \, g \, I_z}{L} \; \frac{\text{volt-sec}}{\text{turn}}$$

5.2 The Voltage Induced by Atomic Polarization

The last form is a direct indication of the voltage/turn that would be generated if ϕ_{int} were built up linearly in one second.

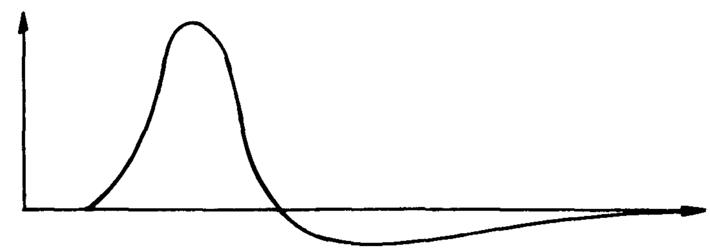
If we now consider a gas sample for which L = 6 cm = 0.06, and with $N_{I_z} = 10^{18}$, $g\,I_z = 1$, we have

$$\phi_{int} = 2 \times 10^{-10} \; \frac{\text{volt-sec}}{\text{turn}}$$

If ϕ_{int} is built up over a microsecond, this would generate 2×10^{-4} volt/turn; or over a millisecond 2×10^{-7} volts/turn.

As laser discharge times and gaseous relaxation times are of this order, obtaining these voltages depends on whether $N_{I_z} \approx 10^{-18}$ is a realizable figure.

The voltage signal from a multi turn coil wrapped around the sample could be displayed on an oscilloscope. If for instance the pumping took place in a microsecond, and the relaxation time was several times longer, one might expect a track, as shown in figure II-3, where the peak represented $10^6\, n\, \phi_{int}$ volts, with n the number of turns.



1 μsec polarization build up   decay

5.3 Absorption in Gaseous Sample

If the sample absorbs an energy W, the excitation of states with excitation energy E, the number of atoms oriented (if the relaxation time is long compared to the discharge time) is $\frac{W}{E}$. If a one Joule discharge is absorbed by a 1 ev excitation, we have

$$N_{I_z} = \frac{W}{E} = \frac{1}{1.6 \times 10^{-19}} = 0.6 \times 10^{19}$$

of the order used in paragraph 5.2. Therefore, we need to produce a Joule of power within a millisecond in the resonance width. Below we consider the problems in the absorption of large amounts of pumping energy.

5.3.1 The most obvious means of alignment by means of optical pumping is to irradiate the sample with a strong external source. If the source is a laser emitting the needed frequency, the result would be the feeding of more power in a short time to the sample than possible with an incoherent lamp. As the excited state would decay too quickly by a radiative transition ($\sim 10^{-8}$ sec) preventing build-up, one would rely on the decay resulting in an aligned ground or metastable state.

A laser beam can easily be concentrated within the 1 cm^2 cross section proposed for the gaseous sample. We will show below that the radiation within the resonance will be absorbed within a very short distance in a gas sample of a density consistent with relaxation requirements. The process of absorbing the burst of radiation in the whole sample will then consist of successive "hole burning" of the line in thin layers of the gas, making each succeeding layer transparent to the radiation as the excitation is saturated. The whole of the radiation within the resonance will be absorbed if the number of atoms exceeds the number of photons. All the atoms will be oriented if the number of photons exceeds the number of atoms, and if the relaxation time is long compared to the time of transit of the pumping beam.

The absorption is estimated as follows. The cross section of an atom for the absorption of a photon at a resonance maximum, if the line has the natural width, is

$$\sigma_m = \frac{2\pi c^2}{\nu_o^2} f = \frac{f}{2\pi k_o^2}$$

where ν_o is the frequency, k_o the wave number of the photons at the peak, and f is the oscillator strength. The radiated line will have close to the natural width in a coherent laser beam. However, the gaseous sample absorption line will have the Doppler width in addition; as the latter is much larger it will dominate, and the effective cross section is reduced from σ_m by the ratio of the natural width γ to the Doppler width δ. We have

$$\frac{\gamma}{\delta} = \frac{4\pi c^2 k_o}{3 m_e c^2} \sqrt{\frac{Mc^2}{2K\,T \log 2}}$$

where M is the atomic mass, K is Boltzman's constant, and T is the temperature. Therefore,

$$\sigma_{eff} = \frac{2\, e^2\, f}{3\, M_e\, c^2\, k_o} \sqrt{\frac{M_e^{\,2}\, c^2}{2\, K\, T \log 2}}$$

$$= \frac{2f}{3} \left(\frac{e^2}{h_c}\right) \sqrt{\frac{Mc^2}{2\, K\, T \log 2}} \left(\frac{1}{k_o}\right) \left(\frac{h}{M_e c}\right)$$

$$= \frac{2 \times 0.1}{3 \times 137} \sqrt{\frac{10^{10}\ \text{ev}}{500 \times 10^{-4}\ \text{ev}}} \times 10^{-4}\ \text{cm} \times 10^{-11}\ \text{cm} \approx 2 \times 10^{-13}\ \text{cm}^2$$

where we have used k_o corresponding to 1 ev and an oscillator strength of 0.1. This implies that 10^{13} atoms/cm^2 will absorb the radiation completely. 10^{18} atoms in a 1 cm^2 cross section tube will then be saturated by the line in a very short fraction of the length of the tube. That layer will then be transparent, permitting the radiation to go to the next layer and be absorbed there.

5.3.2 In principle, one can use the alignment that occurs in the laser material when it develops a directed or circularly polarized laser beam. The previous discussion shows how one may produce a controlled polarization of the cascade by the use of a Faraday active end plate in the laser cavity. Indeed, it is difficult to avoid linear or circular polarization in a laser beam, due to asymmetry of the cavity. Striations in the original Javan He-Ne laser produced a steady linearly polarized beam.[7] Other experiments have reported unstable circular polarization occurring in more symmetric cavities. A simple magnetic Zeeman splitting of the states would be likely to favor one polarization over another although this would be small for ordinary stray fields. The production of the polarized cascade appears to present no difficulty.

In this case it would be the emission of radiation by the atoms, rather than absorption, that would align them. The general energy requirements would be

---

[7] W. R. Bennett, Jr., Phys. Rev., 126, 580 (1962).

the same as those in the absorption cell. Complete use of the beam is assured, as each photon in the beam results in the population of the laser states.

A disadvantage of this method is the low intensity of presently available gaseous lasers compared to solid state lasers. Another difficulty arises in the fact that some of the available gaseous lasers are pumped by electric discharge (He-Ne). The current so produced would overwhelm the magnetic moment due to polarization. The C. W. gaseous laser would appear to offer no advantage, as the larger voltages are induced by much energy being absorbed or emitted in a short time. The C. W. lasers are low power devices at present.

5.4 Relaxation Time

We have assumed that the aligned state is a ground or metastable state so that radiative decay to other levels may be ignored in the relaxation time. There remains the possibility of radiative decay to other I_z sublevels (which may be non-degenerate due to the presence of magnetic fields). These would have to be decays with no parity change, and would therefore also be slow.

There remains the relaxation phenomena due to interatomic collisions and atomic-wall collisions. The conservation of angular momentum in interatomic collisions may lead to speculation that the magnetic moment would not be greatly altered. However, the relative nuclear-electronic angular momenta will usually be changed, leading to random changes in the electronic angular momentum. As the small nuclear magneton may be neglected, on the average the magnetic orientation is destroyed.

Under normal conditions we may consider every atom that collides with the wall to be disoriented. This puts an upper limit to the relaxation time obtained by assuming no interatomic collisions. At room temperature

$$v = C \sqrt{\frac{K\,T}{Mc^2}} \approx 10^5 \text{ cm/sec}$$

In our 1 cm container, this corresponds to a relaxation time of 10^{-5} seconds. When the discharge of the pumping beam takes place over a longer period (perhaps 10^{-3} sec), this relaxation rate would prevent maximum orientation from being attained. This time can be lengthened by coating the walls with Teflon as used in the hydrogen maser work of Ramsey, et al. This coating allows up to 10^5 collisions with the walls before disturbing the atomic structure, permitting one second storage.

It is clear then that we must keep the interatomic mean free path longer than 1 cm to obtain reasonable relaxation times. If we assume that any interatomic collision will disorient the magnetic moments then it is the total or diffusion cross section which is relevant. Due to long range electronic interactions, the diffusion cross section is about an order of magnitude greater than the area of a Bohr radius, i.e., $\sigma_a \approx 10^{-15}$ cm^2. The mean free path is then $(\sigma_a n_a)^{-1}$, where n_a is the atomic density. Therefore

$$n_a <= \frac{1}{\sigma_a \times 1 \text{ cm}} \approx 10^{15} \text{ atoms/cm}^3$$

under our present conditions. In a ten centimeter long tube this is only 10^{16} atoms, two orders of magnitude smaller than we considered in our magnetic field calculations of paragraph 5.2. But, the assumption of the diffusion cross section was an upper limit for the interatomic electronic disorientation cross section. An order of magnitude may easily be available here, most of the collisions leading to linear momentum changes only. We may also increase the relaxation time for a given mean free path by cooling the sample. We may increase the number of atoms for a given relaxation time by increasing the volume of the sample. Gaseous densities of 10^{16} - 10^{17} atoms/cm^3 (10^{-2} - 10^{-1} mm mercury) would then seem to be compatible with relaxation times longer than a μ second and the suggested total of 10^{18} atoms. This is consistent with relaxation times obtained in such experiments as those of Hawkins[8] and of Colegrove and Franken.[9]

[8] Hawkins, Phys. Rev. 98, 478 (1955)

[9] Colegrove and Franken, Phys. Rev. 119, 680 (1960)

5.5 Microwave Orientation

A maser beam of microwave frequency could be used to orient a gas sample in a magnetic field. The Zeeman splitting of the ground state or a metastable state would permit microwave transitions between magnetic sublevels. If the maser beam is polarized it is clear that orientation would result. Of course, one may use the orientation of the atoms in the maser gas itself, if the maser action is due to a Zeeman splitting. If an external beam is used, the Zeeman splitting may be adjusted by changing the magnetic field, until it is tuned to the maser beam frequency. The maser activity may then be due to different levels than those used in orienting the gas. One need not rely on accidental degeneracies.

The biggest advantage in the use of microwave instead of optical frequencies is the much larger number of photons for a given pumping energy. Saturation would be much easier to attain.

The difficulty is the large magnetic field that must be present. However, if it was sufficiently steady, $\frac{d\phi}{dt}$ could be reduced below that of the orientation signal.

6. CONCLUSIONS AND RECOMMENDATIONS

We conclude from the foregoing analysis that it is indeed feasible to construct a laser to operate in a single circularly polarized mode. Although several optical designs are possible, all make use of the Faraday effect in glasses in which there exists a magnetic field. From the design point of view, there appears to be no difficulties to the construction of such a laser; physical estimates of various design parameters, such as magnetic field strength, are all well within reason, so that the circularly polarized laser appears to be well within the capabilities of present technology.

Once such a laser is constructed, and after preliminary experiments are made to verify its performance (such as are described above), the CP laser may prove to be an extremely useful tool for the measurement of hyperfine structure, nuclear g-factors, Zeeman splitting, etc. It seems likely that the application of the CP laser in measurements of this type will be very fruitful, and investigation in that direction should be pursued.